

California's Groundwater Update 2013 - Appendix "E"

Calculating Annual Change in Groundwater Storage Using Groundwater Level Data

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Calculating Annual Change in Groundwater Storage Using Groundwater Level Data

This technical memorandum (TM) describes the method for calculating change in groundwater storage using groundwater levels, as developed by the California Department of Water Resources (DWR) for the California Water Plan (CWP) Update 2013. This method applies custom Geographic Information Systems (GIS) tools to groundwater level data stored in the DWR Water Data Library (WDL) to compute change in storage.

Other related topics, such as determining aquifer characteristics and alternative methods of estimating changes in groundwater storage, are briefly discussed but are limited to their relevance to calculating change in groundwater storage.

1. INTRODUCTION

Recommendations and feedback from the CWP Update 2009 indicated a need for more transparent and reliable methods of estimating changes in groundwater storage. For CWP Update 2013 GIS modeling is used to develop a method for estimating change in groundwater storage using groundwater level data.

1.1. Summary / Background

This TM provides a background and description of the methodology used to calculate the annual change in groundwater storage as reported in the CWP Update 2013 – Groundwater Enhancement Section. Annual Change in Groundwater Storage is the difference in the volume of water in an aquifer from one year to the next. The TM describes how DWR evaluates and processes available groundwater level data to estimate the annual change in groundwater storage within a groundwater basin or reporting area. The change in groundwater storage estimates, based on the methods described in this TM, are intended for evaluating basin-wide issues and are not intended for detailed local analysis that may be required for implementation of specific projects.

Change in groundwater storage has been reported in past California Water Plan updates. However, the reported change number was not directly calculated but was the byproduct of land and water use calculations that estimated overall water use. It was determined that change in groundwater storage values should be directly calculated based on a standardized, repeatable, and transparent methodology from the best available data, instead of estimates based on water demand calculations which did not include all inflows and outflows of the groundwater budget.

1.2. Groundwater Level Data and Geographic Information Systems

A groundwater level measurement collected from a single well provides groundwater level information at a particular location, whereas measurements collected from multiple wells (as in a monitoring network) can provide information about the groundwater levels over an area or region. Changes in groundwater levels can be determined at a single well from repeated measurements, and changes in the groundwater level over a region can be determined from repeated measurements from multiple wells within that region. Changes in groundwater storage can then be estimated from changes in groundwater levels, if enough information is known about the aquifer system.

Geographic Information Systems (GIS) is a system designed to manage, manipulate, analyze and present geographical data, and is well suited to analyze groundwater level data collected from wells. Using custom built GIS tools, a repeatable procedure was developed to process groundwater level measurements from wells, to evaluate changes in groundwater levels and estimate change in groundwater storage. These GIS tools, along with a systematic process of implementing them represent a “workflow” by which groundwater level data is queried, filtered, and analyzed to determine regional groundwater elevations, annual changes in groundwater elevation, and annual changes in groundwater storage.

1.3. Change in Groundwater Storage

Change in groundwater storage describes the difference in groundwater volume between two time periods. Change in groundwater storage is calculated by multiplying the difference in groundwater elevation between two monitoring periods, by the area overlying the

groundwater basin, and the average storativity (specific yield in an unconfined aquifer). The time interval over which the groundwater elevation change is determined is study specific, but annual spring-to-spring changes are used because spring months in California generally represent full basin conditions for the year.

2. DATA TYPES and AVAILABILITY

The process of calculating the change in groundwater storage using groundwater level data requires *well data* and *hydrogeologic data*, in addition to *groundwater level measurement data*. Information about the quality of the data is also needed for confidence in the quality of the results. The data and quality information are obtained from a variety of sources, including Well Completion Reports and other reports filed after the construction of the well, field data collected as part of a monitoring program, and special studies.

2.1. Well Data

Well data is information describing the well's location, construction details, and well use. Information about the materials encountered while drilling, and more detailed information about specific hydrologic properties of the water bearing formations are also typically provided.

2.1.1. Well Completion Reports

A Well Completion Report (WCR) (currently DWR Form 188) is required by Water Code 13751(a) to be completed and submitted to DWR each time a new well is drilled. A WCR contains basic information about the well's intended use, location, construction, owner and driller. A section of the WCR, known as the Well Log, contains information about the subsurface materials encountered during drilling of the well borehole.

The well location and construction details provide spatial information directly related to the water level measurements collected at the well. Information about the well type, well use, and construction date, also contained in the WCR, can be important for evaluating the quality of the data collected at the well.

2.1.2. Other Well Information

In addition to WCR's, other well data may be available. This type of information is sometimes contained in special reports prepared when a particular well or monitoring network is installed, and may include geophysical surveys, historical information, or other data which may also provide information about the quality of collected groundwater level data.

2.1.3. Well Data Availability and Quality

For any given well, the available data varies. Ideally, a Well Completion Report is completed and filed with DWR, the well location and elevation is surveyed, and there is supplemental information about the hydrogeology (such as a geophysical survey). Unfortunately, few of the over 45,000 wells entered into the DWR groundwater level database contain this degree of well data completeness and quality. For a typical well, a WCR exists and some of the well construction information is available (such as well depth), and the well location data is at least within 10 meters. Unfortunately, many wells within the database lack well construction data (or the data is not currently loaded into the database) and the exact well location has not been confirmed in the field. For a well with insufficient data, it may be possible to characterize the water level data by comparing its water level measurements to a neighboring well for which more data exists.

2.2. Groundwater Level Data*

Groundwater levels are one of the key indicators of groundwater basin and aquifer conditions. Groundwater level data can be used to make interpretations regarding hydrogeology, groundwater flow, groundwater supply and sustainability, land use, etc. Groundwater levels fluctuate seasonally due to various inputs and outputs, such as the amount of precipitation, evapotranspiration, and groundwater pumping. Frequent groundwater level measurements provide more detail regarding the seasonal groundwater level fluctuations and aquifer conditions.

Depending on the scope, intent, and goals of a well monitoring network, the measurement frequency can range from multiple times an hour to once a year or longer. Some groundwater

level records include years of data gaps or stop altogether due to lack of funding, well conditions, or site/well access issues.

Groundwater level data are collected by DWR, staff from local agencies, and other individuals. Groundwater level data consists of water level measurements collected from wells, and qualitative information recorded when the measurement was collected. Water levels are measured from a fixed point, known as the “reference point”, using one of a variety of instruments such as a steel tape, electronic sounder, acoustic sounder, or pressure transducer. Qualitative information indicates conditions that may make a measurement questionable or record the reason a measurement was not collected during a site visit.

2.2.1. DWR Water Data Library Groundwater Level Database

Groundwater level data (collected prior to the implementation of CASGEM*) is loaded and managed in an Oracle Database referred to as the DWR Water Data Library Groundwater Module (WDL). Data not loaded into the WDL was not included in the annual change in groundwater storage estimates.

2.2.2. Spatial and Temporal Aspects of Groundwater Level Data

An individual groundwater level measurement is unique both in space and time, and a collection of groundwater level measurements from a well network provides information about how groundwater levels change over time over a region.

2.2.3. Groundwater Level Data Availability

The availability of groundwater level data is variable from region to region over time. For the CWP Update 2013, spring groundwater level data was analyzed for the years 2005 through 2010. Water level data collected from groundwater basins and subbasins statewide was evaluated and it was determined that the WDL did not have sufficient groundwater level data for regions outside the Central Valley to reliably evaluate changes in groundwater storage. For most areas within the Central Valley, sufficient groundwater level data exists in the WDL to estimate changes in groundwater storage. Regions within the Central Valley that lack sufficient

groundwater level data include the delta region and portions along the west side of the San Joaquin Valley.

2.3. Hydrogeologic Data

2.3.1. Storage Coefficients and Other Aquifer Properties

Storativity is a term used to describe the volume of water released from or taken into storage in an aquifer per unit surface area per unit change in hydraulic head. In an unconfined aquifer it is approximately equal to the specific yield. Specific yield represents the water-yielding capacity of a material and is defined as the ratio of the volume of water that will drain by gravity from a saturated rock or soil compared to the total volume of rock or soil. Storativity values are unit less (although sometimes expressed as a percentage) and are influenced by factors such as porosity, mineral grain size, aquifer compaction, cementation, and water quality.

2.3.1.1. Porosity

The porosity of an aquifer represents the total volume of void space in which water can be stored. Specific yield values are closely related to porosity because groundwater is stored in the void space of rocks or soil in an aquifer. Porosity is defined as the ratio of the volume of void space in a rock or soil to the total rock or soil volume. Porosity values are typically expressed in percentages.

The porosity of an aquifer is closely related to the size of the mineral grains and rock fragments in the aquifer. The porosity and mineral grain size affects the amount of water that an aquifer will take in or yield. For more information regarding porosity and other factors affecting specific yield, read USGS Water Supply Paper 1662-D (Johnson, 1967) and California Department of Public Works, Division of Water Resources Bulletin 45 (Eckis, 1934).

2.3.1.2. Methods of Determination

Specific yield values can be determined in the field or laboratory using direct or indirect methods. Direct methods divide the measured volume of water that drains from a volume of saturated material, by the volume of the saturated material. Indirect methods involve determining the specific retention (the percent of water that will not drain from a saturated

material) of a known volume of material after gravity drainage, then subtracting that value from the porosity of the material.

WCRs or drillers' logs may also be used to determine the specific yield of an aquifer. During well construction, drillers typically document the materials encountered while drilling. The materials encountered by the drillers during well construction are assigned numerical specific yield values. A representative number of drillers' logs are usually included to determine the average composition of an aquifer or zones within an aquifer. Then the specific yield values of the materials encountered are averaged to determine the specific yield of an aquifer.

Various methods and assumptions related to determining the specific yield of materials are discussed in DWR Bulletin Number 45 (Eckis, 1934). Determining specific yield values using drillers' logs are discussed in DWR Bulletin Number 45 (Eckis, 1934), USGS Water Supply Paper 1497 (Olmsted and Davis, 1961), USGS Water Supply Paper 1662-D (Johnson, 1967), and the Report of Referee (California State Water Rights Board, 1962).

2.3.1.3. Effect on Groundwater Storage Calculations

Aquifers or groundwater basins in many cases are spread over large areas. Since specific yield values are used to determine the change in groundwater storage of an unconfined aquifer system or groundwater basin, representative specific yield values are important. An unrepresentative specific yield value would result in an inaccurate determination of the change in groundwater storage. The amount of error in the change in groundwater storage determination would increase as the size of the aquifer increases.

The various methods of determining specific yield involve different assumptions and limitations. These assumptions and limitations may produce associated errors in the estimation of specific yield values. See USGS Water Supply Paper 1662-D (Johnson, 1967) for a discussion of these error related issues.

2.3.2. Availability and Application of Specific Yield Data

Many reports, groundwater models, and other scientific documents publish specific yield data for many of California's groundwater basins. Because of the broad regional scope of estimating annual change in groundwater storage for the CWP, specific yield data gathered and reported

for large regions of the State can be useful in lieu of pulling and aggregating information together from many smaller regions. After evaluation of existing reports and models, specific yield values from two models were adapted for use for the work described in this TM; the DWR C2VSIM groundwater/surface water model (2013), and the USGS Central Valley Hydrologic Model (2009). Data from these models were evaluated because they both provide specific yield values for the Central Valley in a geospatial format readily useable in GIS.

2.4. Data Gaps

[This section has been incorporated into other sections of the TM]

3. ALTERNATIVE METHODS USED TO CALCULATE CHANGE IN GROUNDWATER STORAGE

A variety of methods exist to estimate changes in groundwater storage. Several methods are described below for reference and to acknowledge that alternative approaches exist. The myriad of methods used to estimate change in groundwater storage can be generalized into three categories - those that use groundwater level data exclusively; those based on water balances, water budgets or modeling; and those that use remote sensing. Examples from each of these categories are provided below.

3.1. Other Methods that use Groundwater Level Data

3.1.1. USGS Scientific Investigations Report 2012-5291

The recently published USGS report *Water-level and storage changes in the High Plains aquifer, predevelopment to 2011 and 2009-11* (2013, McGuire, Virginia L. *USGS Scientific Investigations Report: 2012-5291*) uses groundwater level measurements to present “water-level changes in the High Plains aquifer from the time before substantial groundwater irrigation development began (generally before 1950, and termed “predevelopment” in this report) to 2011 and from 2009-11. Similar to the approach outlined in this TM, groundwater level data was processed using GIS tools. Groundwater elevations were characterized using rasterized surfaces (developed with GIS) for “predevelopment”, 2009, and 2011. These rasterized surfaces were processed to determine the “saturated thickness” and changes in the saturated thickness of the aquifer. Specific yield values of the aquifer were determined and summarized as a GIS dataset,

then used to process the changes in groundwater storage based on the change in saturated aquifer thickness.

3.2. Methods that use Water Balance / Budget / Modeling

3.2.1. DWR C2VSIM (2013) and USGS CVHM (2009)

The **California Central Valley Groundwater-Surface Water Simulation Model (C2VSim)** is an integrated numerical model that simulates water movement through the linked land surface, groundwater and surface water flow systems in California's Central Valley. The C2VSim model contains monthly historical stream inflows, surface water diversions, precipitation, and land use and crop acreages from October 1921 through September 2009. C2VSim dynamically calculates crop water demands, allocates contributions from precipitation, soil moisture and surface water diversions, and calculates the groundwater pumpage required to meet the remaining demand. The model simulates the historical response of the Central Valley's groundwater and surface water flow system to historical stresses, and can also be used to simulate the response to projected future stresses. C2VSim was developed using the Integrated Water Flow Model (IWFM) Version 3.02. C2VSIM is capable of reporting changes in groundwater storage.

For more information, see

http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/index_C2VSIM.cfm

The **Central Valley Hydrologic Model (CVHM)** was developed by the USGS and is an extensive, detailed three-dimensional (3D) computer model of the hydrologic system of the Central Valley (Faunt *et al.*, 2009). The Central Valley Hydrologic Model (CVHM) simultaneously accounts for changing water supply and demand across the landscape, and simulates surface water and groundwater flow across the entire Central Valley (also see

<http://ca.water.usgs.gov/projects/central-valley/central-valley-hydrologic-model.html>)

The development of the CVHM comprised four major elements: (1) a comprehensive Geographic Information System (GIS) to compile, analyze and visualize data; (2) a texture model to characterize the aquifer system; (3) estimates of water-budget components by numerically

modeling the hydrologic system with the Farm Process (FMP); and (4) simulations to assess and quantify hydrologic conditions.

For more information, see http://pubs.usgs.gov/pp/1766/PP_1766.pdf

3.3. Methods that use Remote Sensing

3.3.1. NASA GRACE

The primary goal of the ***Gravity Recovery And Climate Experiment (GRACE)*** mission is to accurately map variations in the Earth's gravity field. The GRACE mission has twin satellites flying about 220 kilometers apart in a polar orbit 500 kilometers above the Earth.

GRACE maps the Earth's gravitational field by making accurate measurements of the distance between the two satellites, using geodetic quality Global Positioning System (GPS) receivers and a microwave ranging system. This provides scientists from all over the world with an efficient and cost-effective way to map the Earth's gravity fields with great accuracy. The results from GRACE yield important information about the distribution and flow of mass within the Earth and its surroundings.

For more information on GRACE, see <http://science.nasa.gov/missions/grace/>

GRACE can be used to estimate variations in total water storage (TWS) and groundwater storage changes. However, using GRACE data in the Central Valley aquifer can be challenging due to the coarse spatial resolution. Climate variability also alters precipitation, groundwater recharge, and pumping practices. A statistical downscaling approach was applied to GRACE data at the sub-region level and then applied to the downscaled GRACE estimates to investigate the influence of climate variability, such as from the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). Downscaling GRACE-derived groundwater storage estimates using C2VSim data was successful using linear models at the sub-region level. The incorporation of downscaling for estimating variations in groundwater storage in highly productive aquifers may improve water management techniques in California.

For more information on downscaling GRACE, see

<http://www.earthzine.org/2012/08/13/downscaling-grace-data-in-the-central-valley-aquifer-in-california/>

4. USING GROUNDWATER LEVEL DATA TO ESTIMATE CHANGE IN GROUNDWATER STORAGE

4.1. Synopsis

DWR is implementing new methods to analyze groundwater level data and report groundwater levels, and changes in groundwater levels and changes in groundwater storage over time. This TM serves to describe the applied methods and assumptions.

4.2. Goals and Approach

The primary goal of this method is to analyze groundwater level data to estimate the annual change in groundwater storage using groundwater levels measured from wells with a repeatable and transparent process (workflow). Reports will be comparable, as much as practicable, to other methods of estimating changes in groundwater storage.

To meet the goal as described above, an automated process to query, analyze, and report groundwater level data was developed using ESRI map-based ArcGIS software. Using GIS software also facilitated data quality assurance and quality control by enabling the data to be viewed in a map with associated attribute information. The automated process is the implementation of numerous custom designed GIS geoprocessing tools operated in a highly organized workflow. This approach is intended to provide the most direct depiction of the available groundwater level data, minimizing bias.

4.3. Assumptions and Other Key Concepts

A number of important assumptions allow direct processing of groundwater level data in the process workflow. These assumptions enable the process workflow to produce more reliable results and ensure the repeatability of the analysis.

4.3.1. Assumptions

There are eight assumptions, as shown below:

- 1) All data must reside in the DWR Water Data Library*
- 2) Wells are not preselected for analysis. All groundwater level data is initially considered high quality data, appropriate for inclusion in the analysis. Poor quality data is filtered or otherwise removed as needed during the process workflow.
- 3) Groundwater levels represent unconfined, static, water table aquifer conditions
- 4) Only “spring to spring” annual changes in groundwater storage are estimated.
- 5) Groundwater level change is calculated from two water level measurements in the same well**
- 6) The extent, or geographic limit, of the groundwater basin is delineated and it is assumed that no changes in groundwater elevations occur at this boundary.
- 7) The extent, or geographic limit, of available groundwater level data is delineated.
- 8) Specific Yield values are applied as an average for an entire Reporting Area**

*4.3.1.1. All data must reside in the DWR Water Data Library**

The DWR WDL is the Department’s primary repository for groundwater level measurements collected from wells. At this time, data from outside the WDL cannot be included in the process workflow to provide reliable, transparent, and repeatable analysis with the custom built GIS geoprocessing tools.

4.3.1.2. Wells are not preselected for analysis. All groundwater level data is initially considered high quality data, appropriate for inclusion in the analysis. Poor quality data is filtered or otherwise removed as needed during the process workflow.

The WDL contains over 45,000 wells and millions of groundwater level data records collected since the 1920’s. New wells and new water level measurements are being added to the database regularly. Specific information about each well, and the period of measurement for each well is variable and prevents the reasonable pre-selection of wells for the purpose of analyzing groundwater level changes over time. In other words, it is not possible to pick a set of wells to analyze change in groundwater storage over time based on single set of criteria. The GIS workflow and geoprocessing tools were designed also to facilitate evaluating the quality of the groundwater level data. Wells and/or individual measurements can be flagged and removed, or “excluded”, from analysis if they do not meet specific analytical requirements, or are deemed as questionable or erroneous. By utilizing this “inclusive” approach to well and

groundwater level measurement selection, all available data is reviewed, allowing a more robust dataset for conducting analysis.

4.3.1.3. Groundwater levels represent unconfined, static, aquifer conditions

Aquifers are dynamic hydrologic systems influenced by surface and subsurface groundwater inflows/outflows and from groundwater pumping. In order to minimize the effects of these variable conditions, groundwater elevation measurements are filtered to depict “static” conditions in the unconfined portion of the aquifer.

4.3.1.4. Only “spring to spring” changes in storage are estimated

For the purposes of this TM, and for annual change in groundwater storage reports in the CWP, “spring” is a term used generally to describe the period in time before the primary irrigation season. Because of variations in irrigation patterns throughout the State, this period may actually range from January through April. The “spring” pre-irrigation period best represents static groundwater level conditions since it typically allows an aquifer the most time to recover from the previous irrigation season (typically summer or fall of the previous year). Thus, spring to spring changes in groundwater elevations are used in order to minimize the effects groundwater pumping and other inflows/outflows have on groundwater levels. Groundwater level change is calculated from two water level measurements in the same well** Changes in groundwater levels for a basin are derived from the changes in water levels as measured in wells.

4.3.1.5. The extent, or geographic limit, of the groundwater basin is delineated and it is assumed that no changes in groundwater elevations occur at this boundary

The lateral geographic extent of a groundwater aquifer is defined as the outermost edge of the groundwater basin. It is assumed that groundwater levels do not vary at the basin’s edge. In other words, the change in groundwater elevation between any two time periods at the outermost edge of the groundwater basin is equal to zero (this boundary is referred to as the “zero” boundary).

4.3.1.6. The extent, or geographic limit, of available groundwater level data is delineated

It is necessary to describe the extent, or geographic limit, of groundwater level measurements for any change in groundwater storage analysis. In most cases, the extent of the available data will lie within the extent of the groundwater basin.

*4.3.1.7. Specific Yield values are applied as an average for an entire Reporting Area***

Reporting Areas are user defined geographic regions. To estimate the change in groundwater storage between any two time periods within a reporting area, the average specific yield for the reporting area is used. For the CWP Update 2013, average minimum and maximum specific yield values were used to calculate a range in the amount of change in groundwater storage for each reporting area.

4.3.2. Key Concepts

There are seven key concepts utilized in the process workflow, as listed below:

- 1) Groundwater Basin and Subbasin Boundaries
- 2) Reporting Areas and Non-Reporting Areas
- 3) Depth to groundwater and groundwater elevation
- 4) Selecting unique groundwater level measurements
- 5) Groundwater level surfaces
- 6) Change in groundwater level
- 7) Change in groundwater storage

4.3.2.1. Groundwater Basin and Subbasin Boundaries

A groundwater basin is defined as an alluvial aquifer with reasonably well-defined boundaries in a lateral direction and a definable bottom. Lateral boundaries are features that significantly impede groundwater flow such as rock or sediments with very low permeability or a geologic structure such as a fault. Bottom boundaries would include rock or sediments of very low permeability or the base of fresh water (adapted from Bulletin 118, 2003).

A subbasin is created by dividing a groundwater basin into smaller units commonly for the purpose of collecting and analyzing data. The limiting rule for a subbasin is that it should not cross over a groundwater basin boundary (adapted from Bulletin 118, 2003).

For the purposes of CWP Update 2013, the change in groundwater storage is only estimated for alluvial aquifers. Because of the difficulty of adapting the developed method for fractured rock aquifers, calculations were not done for such aquifers.

4.3.2.2. Reporting Areas and Non-Reporting Areas

Reporting areas are discrete areas within a groundwater basin or subbasin used to report change in groundwater elevation and change in groundwater storage estimates. Non-reporting areas are areas that may be of interest, but are outside of a reporting area. For example, a non-reporting area may be a part of a groundwater basin where groundwater elevation data is limited or otherwise not available.

4.3.2.3. Depth to groundwater and groundwater elevation

The depth to groundwater is the measured vertical distance to water in a well from a defined reference point. The depth below ground surface (DBGS) is the depth to groundwater minus the distance from the reference point to the ground surface. Often the reference point is the top edge of the well casing which is commonly above the ground surface. The depth to groundwater and DBGS is commonly expressed as a positive number. However the DBGS can be a negative number if the water level in a well casing is above the ground surface.

The groundwater elevation or water surface elevation (WSEL) is the ground surface elevation minus the DBGS. Negative WSEL values indicate that groundwater levels are below mean sea level.

4.3.2.4. Selecting Unique Groundwater Level Measurements

The measurement frequency among wells is variable, and can range from several times a day to once a year (or even once every several years). Therefore, an individual well may have none, one, or several measurements for any given time period. The process of building groundwater level surfaces requires that a single, or unique, groundwater level measurement is selected from each well. This is accomplished by first selecting all measurements within a defined date range for a given well, then picking the unique measurement that is closest in time to a defined “target date.”

4.3.2.5. Groundwater Level Surfaces

A groundwater level “surface” is a virtual surface built with GIS tools using unique groundwater level measurements collected from wells within a specific time period and region. These unique measurements are imported into a map as point data and used to construct a Triangulated Irregular Network (TIN) with GIS tools. “TINs are a form of vector-based digital geographic data and are constructed by triangulating a set of vertices (points). The vertices are connected with a series of edges to form a network of triangles.” (Environmental Systems Research Institute (ESRI)) For each spring time period, two surfaces are built - a) groundwater levels in an unconfined aquifer (often described as the water table) as the water surface elevation (WSEL) and b) the depth below ground surface (DBGS). The WSEL and DBGS surfaces are generally depicted in maps as contours and/or with color ramping.

4.3.2.6. Change in groundwater level

Groundwater level changes in an unconfined aquifer can be measured by monitoring the changes in groundwater levels in selected wells that intercept an unconfined aquifer. The change in groundwater levels between two distinct time periods is simply determined by calculating the difference in the water levels measured in each time period. If water levels rise over time, the difference is expressed as a positive number, and if water levels drop then the difference is a negative number. The spring to spring annual change in groundwater elevation is calculated by subtracting the later spring measurement from the earlier spring measurement. GIS tools can be used to express the calculated change (or difference) in water level measurements as a surface, just as the WSEL and DBGS can be expressed as a surface. The change in water levels can be represented in a map with contoured isolines and/or with color ramping indicating the amount of water level change.

(Note that GIS tools can also determine the difference between two TIN surfaces, such as WSEL surfaces. For the CWP Update 2013 the change in groundwater levels is determined by comparing measurements in wells (represented as points), rather than by comparing groundwater level surfaces directly.)

4.3.2.7. Change in groundwater storage

The change in groundwater levels between two time periods (as measured from wells intersecting an unconfined aquifer) represents a thickness within the unconfined aquifer. This thickness, over a defined area, represents a volume of aquifer space in which groundwater levels have changed over time. The amount of groundwater within a volume of aquifer space is estimated by applying the storage coefficient (Specific Yield, S_y). For the CWP Update 2013 a minimum and a maximum S_y are applied to the change volume of an unconfined aquifer within a defined “reporting area.” The minimum and maximum S_y values selected are 0.07 and 0.17, respectively. The amount of estimated change in groundwater storage for any given reporting area is provided as a range of values based on the applied minimum and maximum S_y values.

4.4. Workflow Process

Calculating the change in groundwater storage using groundwater level data can be divided into several distinct, related steps in the workflow process. For each of these steps, one or more custom GIS geoprocessing tools were developed.

4.4.1. Query and filter groundwater level data for “spring” datasets

A spring groundwater level data set is a list of wells, each with a single unique water level measurement, and other pertinent information. Wells are not all measured on the same day or at the same frequency, and querying a single measurement per well for the spring dataset is a multistep process. Selecting the well and the unique measurement is accomplished with a series of GIS tools which filter data based on several input parameters, as shown in Table ?? below.

Parameter	Data Description	Purpose
Geographic Region	Polygon feature	Limits the geographic scope of the query
Date Range	Minimum date value and maximum date value	Selects only well data within a specific date range
Target Date	Date	Selects the water level

		measurement nearest the specified target date
Well Depth	Depth, in feet	Filters wells by depth
Questionable Measurement Code	Coded values (alphanumeric)	Filters out measurements with specific measurement quality codes (such as “well is pumping” or “pumping well nearby”)
Excluded Wells	Table of “bunk” wells and associated codes	Removes wells that are listed on the Excluded Wells table

For the CWP Update 2013, each spring dataset was limited to a geographic region described by the B-118 groundwater basins within the Central Valley. For wells within this region, groundwater levels between January 1st and May 30th were queried. Where more than one measurement for a given well exists within this date range, the measurement on the date closest to the target date of March 15th was used.

There are numerous checks built into the workflow process to evaluate the quality of the well and water level data. Although the workflow is designed to automatically minimize the use of poor quality or inappropriate data, occasionally a bad data point is discovered during the development of point datasets, groundwater level surfaces, change surfaces and change in storage estimates. It is important that these data be isolated and removed, and that their removal properly documented. When one of these bad data points is identified, it is added to the “excluded wells table.” The excluded wells table catalogs questionable or otherwise inappropriate data, along with a coded value and a comment.

After a spring dataset is created using the date range and target date filters, the remaining well points are then compared to the “excluded wells table.” Generally, wells in the excluded wells table are then removed from the spring dataset.

4.4.2. Create groundwater level surfaces within defined basins

Surfaces representing regional groundwater elevations and depth of groundwater below ground surface are created from the spring dataset. These surfaces are built using a TIN where each water level measurement represents a point in three dimensional space, where latitude and longitude are the X, Y, locations and the groundwater elevation is the Z location. Contour lines and other surface representations can then be built from the groundwater elevation TIN. Surfaces representing groundwater levels provide a powerful tool for data quality assurance and checking by displaying the water level data in a 3-D map environment. For example, water level measurements that are not consistent with nearby measurements deviate from the surface model as a spike or a hole. Specific information about these anomalous points, such as measurement date, well construction, and other attributes, can then be reviewed. Any point that does not reliably represent the groundwater level or is otherwise questionable is removed from the surface and is added to the excluded wells table. The surface is then regenerated without the errant points.

For map presentations and reports, the surface model can then be converted to a raster surface, resulting in smooth contour lines.

4.4.3. Calculate change in groundwater elevation over time

The change in groundwater elevation over time is determined by comparing the difference in elevations from points used to build two different groundwater elevation surfaces. Points from the two TIN surfaces are compared, and the difference in elevation is calculated from like points (wells with measurements in both groundwater elevations surfaces). The calculated difference at each of these points represents the net change in groundwater elevation that occurred between the two time periods. Points representing the change between two different groundwater elevation surfaces from two different time periods are sometimes referred to as “change points.” Change points are used to create a new TIN which represents the amount of groundwater elevation change between two time periods within a given region.

4.4.4. Calculate intermediate volumes using surface models and basin boundaries

A calculated intermediate volume is the total volume of the space described by the vertical distance (or change) between two groundwater elevation surfaces and a “zero” boundary. The distance between two groundwater elevation surfaces from two different time periods is determined from the “change points.” The outer extent of groundwater elevation change is characterized as a boundary, called the “zero” boundary, and is where changes in groundwater elevation do not occur. The “zero” boundary typically represents the outer edge of the groundwater basin.

The intermediate change volume is built as a TIN model using the change points and the zero boundary. The change TIN actually represents a thickness (or distance in Z space) rather than a surface, as with the groundwater elevation surface model TINs. GIS tools are then used to calculate the intermediate change volume for any region, such as a groundwater subbasin, as long as that region exists within the zero boundary. Note that the average groundwater elevation change for a region can also be calculated by dividing the change volume for that region by the area of the region.

Within the Central Valley, there are some areas in groundwater basins and inside the “zero” boundary where groundwater elevation data is unavailable for analysis. It was deemed inappropriate to estimate changes in groundwater storage where no groundwater data exists, so groundwater basins and subbasins were characterized as reporting areas and non-reporting areas based on available data. The intermediate change volume, as well as the average change in groundwater elevations, is then estimated for each reporting area within a groundwater subbasin.

4.4.5. Apply storage coefficients to calculate change in groundwater storage values

Storage coefficients are used to calculate the volumetric change in groundwater storage from the intermediate change volume. In an unconfined aquifer, the storage coefficient is represented as the specific yield of the aquifer (a unit less number that describes the volume of water that could flow out of a unit volume of aquifer). Large specific yield values generally indicate coarse-grained aquifer materials, while smaller values indicate fine-grained aquifer

materials. The estimated volume of groundwater change between two time periods for each reporting area is calculated by applying a specific yield value to the intermediate change volume.

Because specific yield values cannot be accurately estimated for much of the Central Valley, the estimated change in groundwater storage for the California Water Plan Update 2013 is given as a range of values by applying a minimum and a maximum specific yield value to the intermediate volume. The minimum and maximum specific yield values selected are 0.07 and 0.17 respectively, based on an analysis of DWR C2VSim and USGS CVHM data. For each reporting area a minimum and a maximum estimated change in storage are calculated, as well as an average change in groundwater elevation.

[THE FOLLOWING SECTIONS ARE STILL BEING DEVELOPED]

5. RESULTS / validation

5.1. Comparison with C2VSIM? GRACE? Local model (Kings River? RWA/SGA? DWR water balance?)

5.2. Difficulties in comparing change in storage from different processes

6. Planned improvements in the GIS model

7. RECOMMENDATIONS

7.1. Data Availability

7.1.1. Outside of Central Valley

7.2. Improvements in GIS model function